Cone Penetration Testing for Seismic Hazards Evaluation in Mid-America

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Introduction:

This report documents the cone penetration testing (CPT) conducted for the purpose of mapping seismic ground hazards and soil properties at selected sites in Missouri, Arkansas and Tennessee in the year of 2001. Prior work was reported for USGS Grant 00HQGR0025. The sites have been selected and coordinated with the assistance of other USGS researchers and members of the Center for Earthquake Research & Information (CERI) and the Mid-America Earthquake (MAE) Center.

Three types of vertical cone soundings were conducted during the investigations, including piezocone, seismic piezocone (SCPTu), and resistivity piezocone (RCPTu). The collected data have been used for site characterization and liquefaction evaluation of the subsurface materials. Field testing was conducted by Alec McGillivray, Guillermo Zavala, and Tianfei Liao of Georgia Tech.

In addition to the field testing, several seminars, presentations, and workshops of our USGS research were presented.

Purpose:

In these initial studies, a cone penetrometer system has been used to obtain both geotechnical and geophysical measurements at the same locations in order to facilitate data collection in the New Madrid Seismic Zone. The soundings performed in this study are in conjunction with seismic ground hazard mapping for the purposes of delineating the presence and extent of liquefaction-prone soils, providing shear wave velocity data for site amplification analyses; and obtaining forensic information on the geostratigraphy and source sands at pre-mapped paleoliquefaction sites.

Test Sites:

The test sites include: (1) Nodena Farm at Wilson, AR; (2) Hillhouse Farm at Wyatt, MO; (3) Memphis, TN; (4) Dexter, MO; (5) St. Louis, MO. The map in the following page indicates the general location of all the soundings performed during 2001.

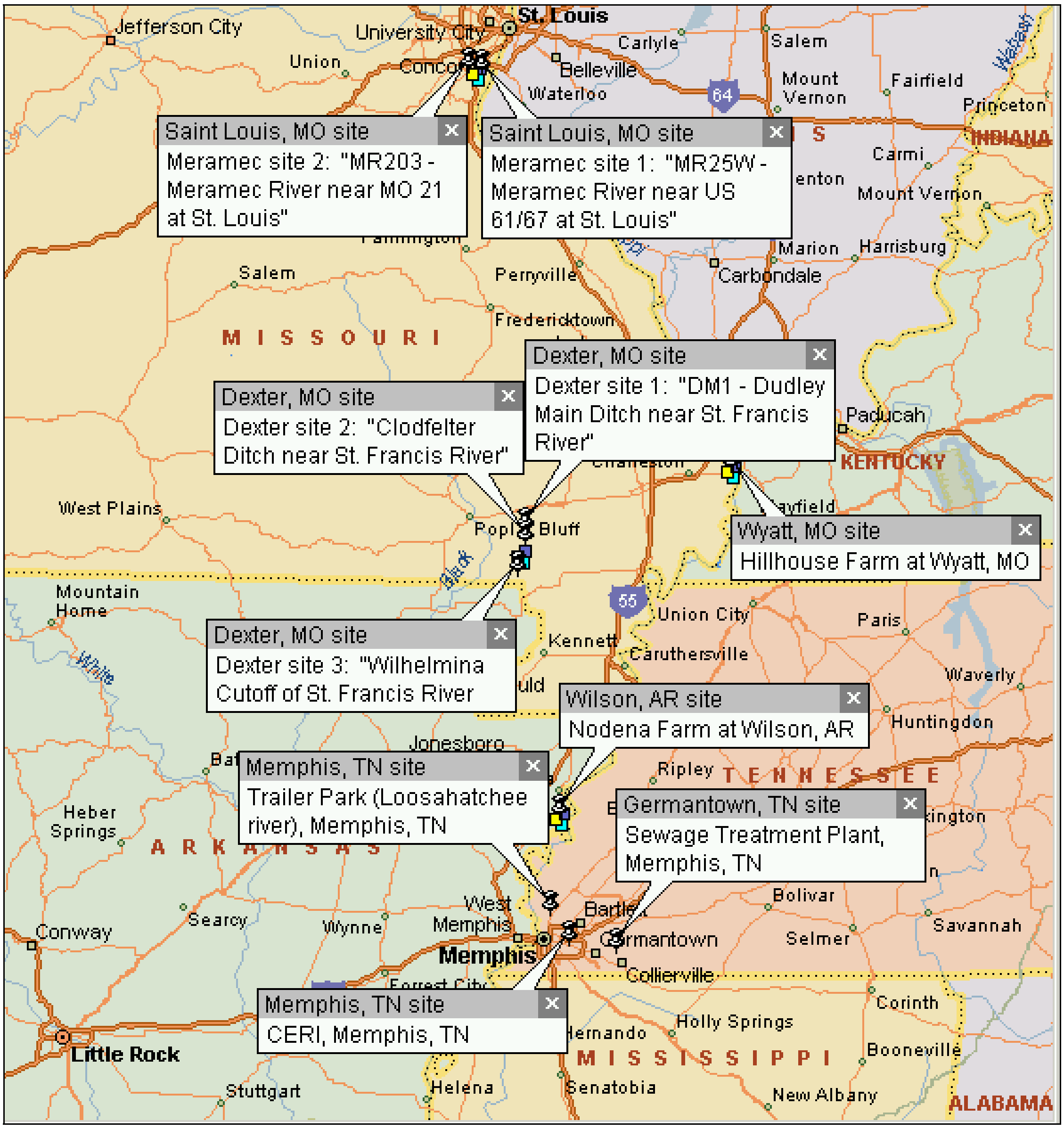

Figure 1. Map showing the location of the soundings performed during 2001

Nodena farm test site, Wilson, AR:

The Upper Nodena site is a paleoliquefaction site located northeast of Wilson, Arkansas. Archeological investigations had previously been performed to study liquefaction features (Tuttle, 1999). Four CPT soundings were performed in a linear array. The site arrangements were coordinated by Martitia Tuttle of M. Tuttle & Associates, Georgetown, ME, Dr. Buddy Schweig of the USGS, and Laurel Mayrose of the University of Memphis.

Soundings at Nodena Farm, Wilson, AR

Sounding	Latitude N°	Longitude W°	Depth (m)	Cone Type
WILS02	35.60202	89.97719	21.43	10 ton cone, u2, seismic
WILS04	35.60208	89.97722	16.20	10 ton cone, u2
WILS06	35.60215	89.97715	22.93	10 ton cone, u1, resistivity
WILS07	35.60217	89.97711	16.43	10 ton cone, u2

Hillhouse farm test site at Wyatt, MO:

The Hillhouse farm is a paleoliquefaction site located in Wyatt, Missouri, just east-northeast of Sikeston, Missouri. Sand blows and other liquefaction evidence were found by previous researchers. The liquefaction features were subjected to archeological investigations, which included trenches to profile the sand dikes (Tuttle, 1999). The CPT soundings were distributed around the edge of the site. Site arrangements were made by Martitia Tuttle and Laurel Mayrose.

Soundings at Hillhouse Farm, Wyatt, MO

Sounding	Latitude N°	Longitude W°	Depth (m)	Cone Type
WYAT01	36.92609	89.15822	25.30	10 ton cone, u2, seismic
WYAT03	36.92685	89.15717	12.03	10 ton cone, u2
WYAT04	36.92706	89.15572	23.00	10 ton cone, u2, resistivity
WYAT05	36.92740	89.15610	19.63	10 ton cone, u2, resistivity

Testing in sites close to Memphis, TN:

Seismic piezocone tests were done at a sewage treatment plant on the banks of the Wolf River near Germantown, Tennessee, and in a small housing community on the banks of the Loosahatchee River in the northwestern part of Memphis, Tennessee. While no liquefaction features were ever documented at these specific locations, the general areas are known to have experienced seismicity in the past. The testing at the Wolf River and Loosahatchee River was arranged by Roy Van Arsdale, Professor of Geology at the University of Memphis.

Soundings at Wolf River site, Germantown, TN

Sounding	Latitude N°	Longitude W°	Depth (m)	Cone Type
SWG01	35.09335	89.71093	28.58	10 ton cone, u2, seismic
SWG02	35.09333	89.71091	30.35	10 ton cone, u2, seismic

Soundings at Loosahatchee River site, Memphis, TN

Sounding	Latitude N°	Longitude W°	Depth (m)	Cone Type
TRPK01	35.23957	90.02412	14.95	10 ton cone, u2, seismic
TRPK02	35.23957	90.02412	15.05	10 ton cone, u1, resistivity

Testing at CERI Headquarters, Memphis, TN:

Two seismic piezocone soundings were performed next to the 100-meter accelerometer array, which is installed at the headquarters of CERI in Memphis, TN. The soil strength characteristics and shear wave velocity obtained are necessary for analysis of the acceleration history should a seismic event occur. Dr. Paul Bodin of CERI assisted in this testing.

Soundings at CERI, Memphis, TN

Sounding	Latitude N°	Longitude W°	Depth (m)	Cone Type
CERI03	35.12366	89.93169	10.18	10 ton cone, u2, seismic
CERI04	35.12366	89.93169	21.33	15 ton cone, u2, seismic

Testing at the western Lowlands of Southeast Missouri:

Six piezocone soundings were performed at 3 different paleoliquefaction sites near Dexter, Missouri. The tests included three seismic piezocone soundings and three resistivity piezocone soundings. Previous archaeological and paleoseismological investigations were performed at these sites in the period July 1990 to 1991 and are documented in the report by Vaughn (1994). The following tables list the exact locations of the recent soundings. The test locations were selected by David Hoffman, Geologist with the Missouri Department of Transportation.

DM1 – Dudley Main Ditch near St. Francis River, Dexter, MO

Sounding	Latitude N°	Longitude W°	Depth (m)	Cone Type
DEX01	36.70038	90.13251	29.02	10 ton cone, u2, seismic
DEX02	36.70038	90.13251	19.33	10 ton cone, u2, resistivity

Clodfelter Ditch near St. Francis River, Dexter, MO

Sounding	Latitude N°	Longitude W°	Depth (m)	Cone Type
DEX03	36.65318	90.13231	30.03	10 ton cone, u2, seismic
DEX031	36.65321	90.13226	28.90	10 ton cone, u2, resistivity

Wilhelmina Cutoff of St. Francis River, Dexter, MO

Sounding	Latitude N°	Longitude W°	Depth (m)	Cone Type
DEX04	36.53725	90.17570	26.43	10 ton cone, u2, seismic
DEX05	36.53725	90.17570	26.50	10 ton cone, u2, resistivity

Testing close to Saint Louis, MO:

Four piezocone soundings were performed at paleoliquefaction sites along the Meramec River at the south side of Saint Louis, MO. The test site arrangements were made by Ronaldo Luna, Professor of Civil Engineering at University of Missouri, Rolla, David Hoffman with MDOT, and Houda Jadi of University of Missouri, Rolla.

MR25W – Meramec River near US 61/67 at St. Louis, MO

Sounding	Latitude N°	Longitude W°	Depth (m)	Cone Type
MER01	38.45882	90.35043	19.75	10 ton cone, u2, seismic
MER02	38.45882	90.35043	18.68	10 ton cone, u2

MR203 - Meramec River near MO 21 at St. Louis, MO

Sounding	Latitude N°	Longitude W°	Depth (m)	Cone Type
MER03	38.46538	90.41467	12.98	10 ton cone, u2, seismic
MER04	38.46502	90.41460	13.55	10 ton cone, u2, seismic

Probabilistic Liquefaction Evaluation Based on Shear Wave Velocity:

The liquefaction potential calculations have been updated with a probabilistic approach for liquefaction evaluation based on shear wave velocity.

In order to evaluate the liquefaction potential, the impact on the soil from the seismic event must be known or assumed. In liquefaction analyses, the seismic loading is typically expressed in terms of the cyclic stress ratio (CSR). For the common simplified procedures, the cyclic stress ratio is most often expressed as (Seed & Idriss, 1971):

$$CSR = \frac{\tau_{ave}}{\sigma'_{vo}} = 0.65\left(\frac{a_{\max}}{g}\right)\left(\frac{\sigma_{vo}}{\sigma'_{vo}}\right)r_d \qquad (1)$$

where a_{max} is the peak ground acceleration, g is the acceleration of gravity, σ_{vo} and σ'_{vo} are the total and effective vertical stresses, respectively, and r_d is a stress reduction coefficient that accounts for the flexibility of the model soil column. In this paper the r_d recommendations of the NCEER Workshop on Evaluation of Liquefaction Resistance of Soils (1997) were followed. Ordinarily, a_{max} is taken from the appropriate design events for a given project (i.e., the 2%, 5%, or 10% probability earthquake; the maximum credible event for a known fault located a set distance from the site; a code based response spectrum, etc.).

The cyclic resistance ratio (CRR) is the threshold for liquefaction and used to compare the available soil resistance with level of ground shaking represented by the cyclic stress ratio (CSR). In order to compute the CRR, the shear wave velocity is normalized by the effective stress and the fines content is accounted for through the following equation with an earthquake moment-magnitude of 7.5 (Andrus & Stokoe, 2000):

$$CRR_{7.5} = a\left(V_{S1}/100\right)^2 + b\left[1/\left(V_{S1c} - V_{S1}\right) - 1/V_{S1c}\right] \qquad (2)$$

where a=0.03, b=0.9, V_{S1} is the overburden stress-corrected shear-wave velocity and $V_{s1} = V_s \big/ \sigma_{vo}'$ (σ_{vo}' is the initial effective overburden stress), and V_{S1c}=220 m/s for sands and gravels with the fines content FC $\leq$ 5%, and V_{S1c}=210 m/s for sands and gravels with FC = 20%, and V_{S1c}=200 m/s for sands and gravels with FC $\geq$ 35%.

A correction factor K_c can be added to (2) for cemented and old soils (>10,000 years) of high V_{s1} (Andrus & Stokoe, 2000):

$$CRR_{7.5} = a\left(K_c V_{S1}/100\right)^2 + b\left[1/\left(V_{S1c} - K_c V_{S1}\right) - 1/V_{S1c}\right] \quad (3)$$

Average estimates of K_c for Pleistocene-age soils range from 0.6 to 0.8.

Based on the shear wave velocity, a mapping function was proposed relate the safety factor F_s to the liquefaction probability P_L (Juang et al., 2001):

$$P_L = 1/\left[1 + \left(F_s/0.72\right)^{3.1}\right] \quad (4)$$

Where F_s = CRR/CSR. Figure 2 show the curves of CRR for different probabilities of liquefaction based on shear wave velocity respectively.

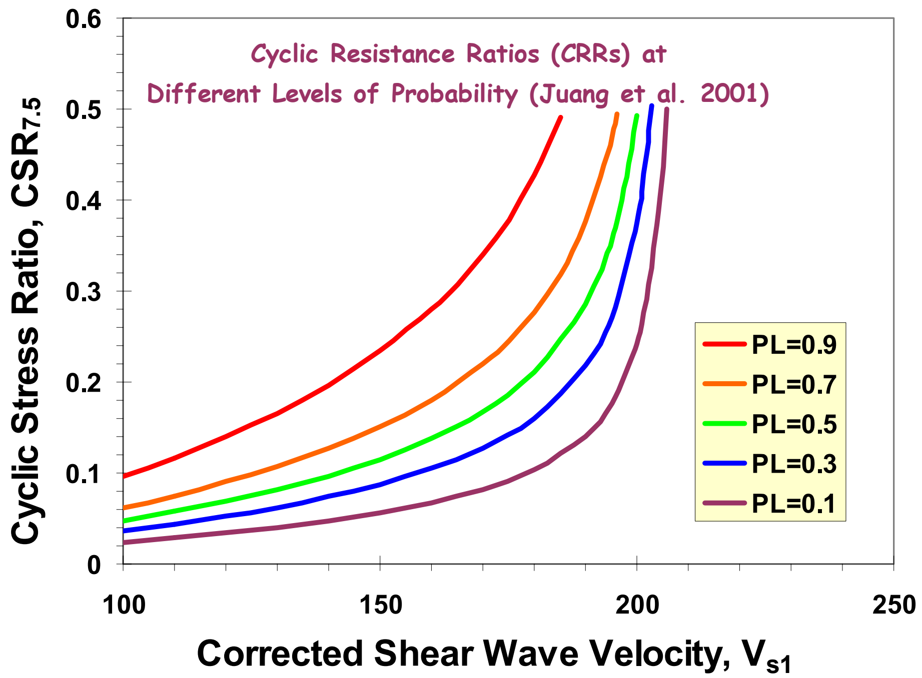

Figure 2. Cyclic Resistance Ratios (CRRs) Based on Shear Wave Velocity at Different Levels of Probability (Juang et al., 2001)

Figure 3 shows the results of liquefaction analysis based on both the tip resistance and shear wave velocity for sounding MER01, which was performed along the Meramec River in St. Louis, MO. The results are presented as the different liquefaction probability versus the corresponding depth under an earthquake magnitude of 8.0. Other magnitude events are also being evaluated. The probability is analyzed based on the tip resistance and the shear wave velocity respectively, as well as jointly. The figure also shows the soil classification for this sounding. According the results of this sounding, it can be seen that though the two approaches, which are based on tip resistance and shear wave velocity, respectively, are independent, they both detected the same regions of high liquefaction probabilities, namely, from 8m to 10m, and from 15m to 20m. They also detected the clayey layer from 11m to 15m, which has zero liquefaction probability. From this example, the analysis result, which are based on the both the tip resistance and shear wave velocity respectively, agrees well to some extent, and the redundant analysis result would enhance the confidence on the conclusion about the liquefaction potential.

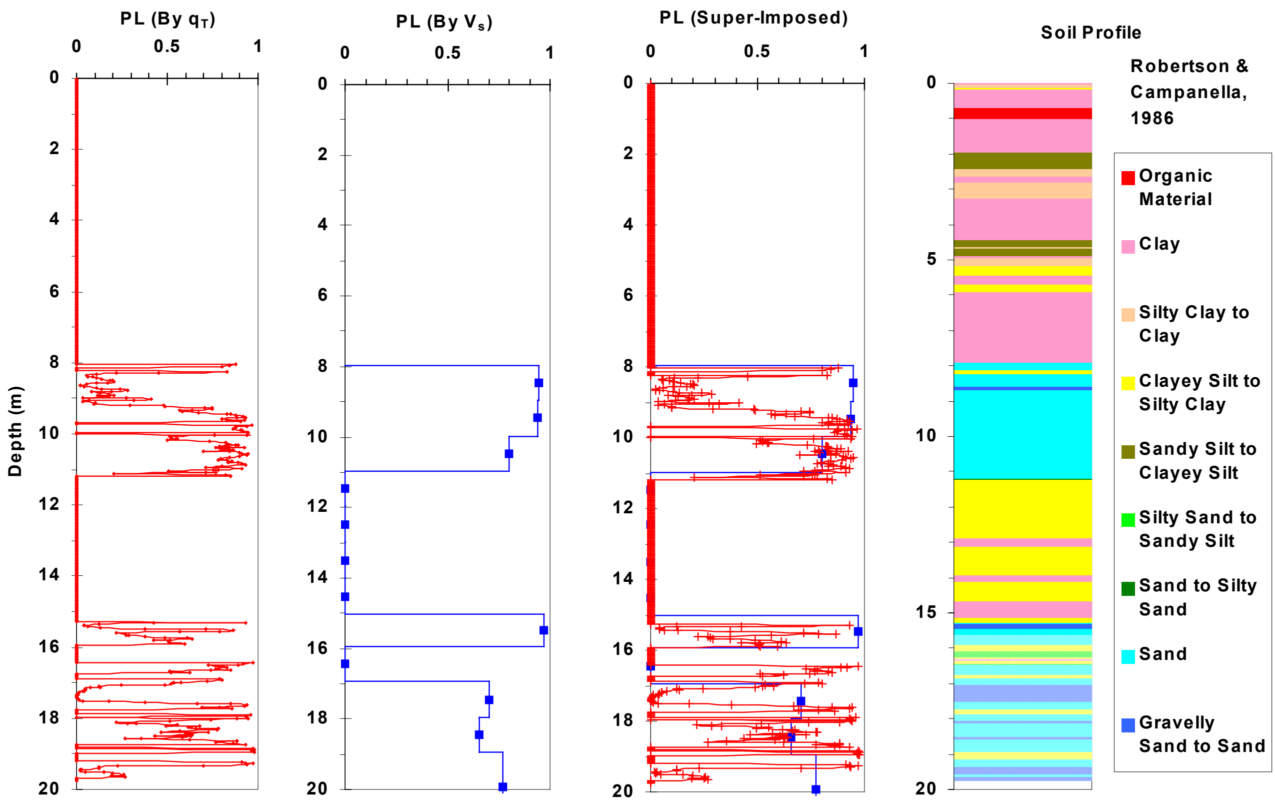

Figure 3. Results of Liquefaction Analysis by Probabilistic Approaches for Souding MER01 Performed along Meramec River in St. Louis, MO

Presentations & Publications:

During the past year, our USGS research has been promoted and presented at the following events:

1. Geotechnical Earthquake Engineering in Mid-America, Dec. 7, 2001, Collinville, Illinois.
2. New Developments in Geotechnical Site Characterization, S&ME Seminar, March 15, 2001 in Charlotte, NC.
3. Geotechnical Earthquake Engineering in Mid-America, March 15, 2001, in Memphis, TN.
4. CPT Workshop by Georgia Tech given in Cape Girardeau to FHWA, MoDOT, IL DOT, MN DOT, and Univ. MO-Rolla, May 2001.
5. Keynote Lecture at In-Situ 2001, Bali, May 2001.

6. Enhanced Site Characterization - Short Course at GeoOdyssey 2001, Blacksburg VA, June 7, 2001.
7. Geotechnical Investigations by Seismic Piezocone, Puerto Rican Engineers Club, San Juan, Aug. 2001.
8. Evaluating Seismic Ground Hazards by Seismic Cone Tests - Soil Dynamics & Earthquake Engineering Conference, Drexel Univ., Oct. 8, 2001.
9. Post-Processing of Shear Wave Data by Cross-Correlation, SDEE'01, Philadelphia, Oct. 9, 2001.
10. Geotechnical Earthquake Engineering in Mid-America, Nov. 15-16, 2001, Charleston, SC.

Publications concerning our research program include the following:

1. Schneider, J.A., Mayne, P.W., and Rix, G.J. (2001). Geotechnical site characterization in the greater Memphis area using seismic cone tests. Engineering Geology, Vol. 62, Issues 1-3, pp. 169-184
2. Liao, T., Mayne, P.W., et al. (2001). Liquefaction Evaluation of Soils in the New Madrid Zone by Cone Penetration Testing, submitted to the Journal of Soil Dynamics & Earthquake Engineering, in review.
3. Zavala, G.J. and Mayne, P.W. (2001). Post-Processing of Downhole Shear Wave Velocities by Cross-Correlation Method, submitted to the Journal of Soil Dynamics & Earthquake Engineering, in review.

Data Availability:

The details of all CPTs performed by Georgia Tech in Mid America have been compiled into a single database. Data searches can currently be performed based on geographic location (latitude and longitude), depth, device specifications, operator, and a number of other items including the availability of seismic or resistivity data. The digital and or graphical results from the CPT field testing program are available at the following site:

http://www.ce.gatech.edu/~geosys/Faculty/Mayne/Research/index.html

These data include downhole shear wave velocity (V_s) data that have been collected at select locations.

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